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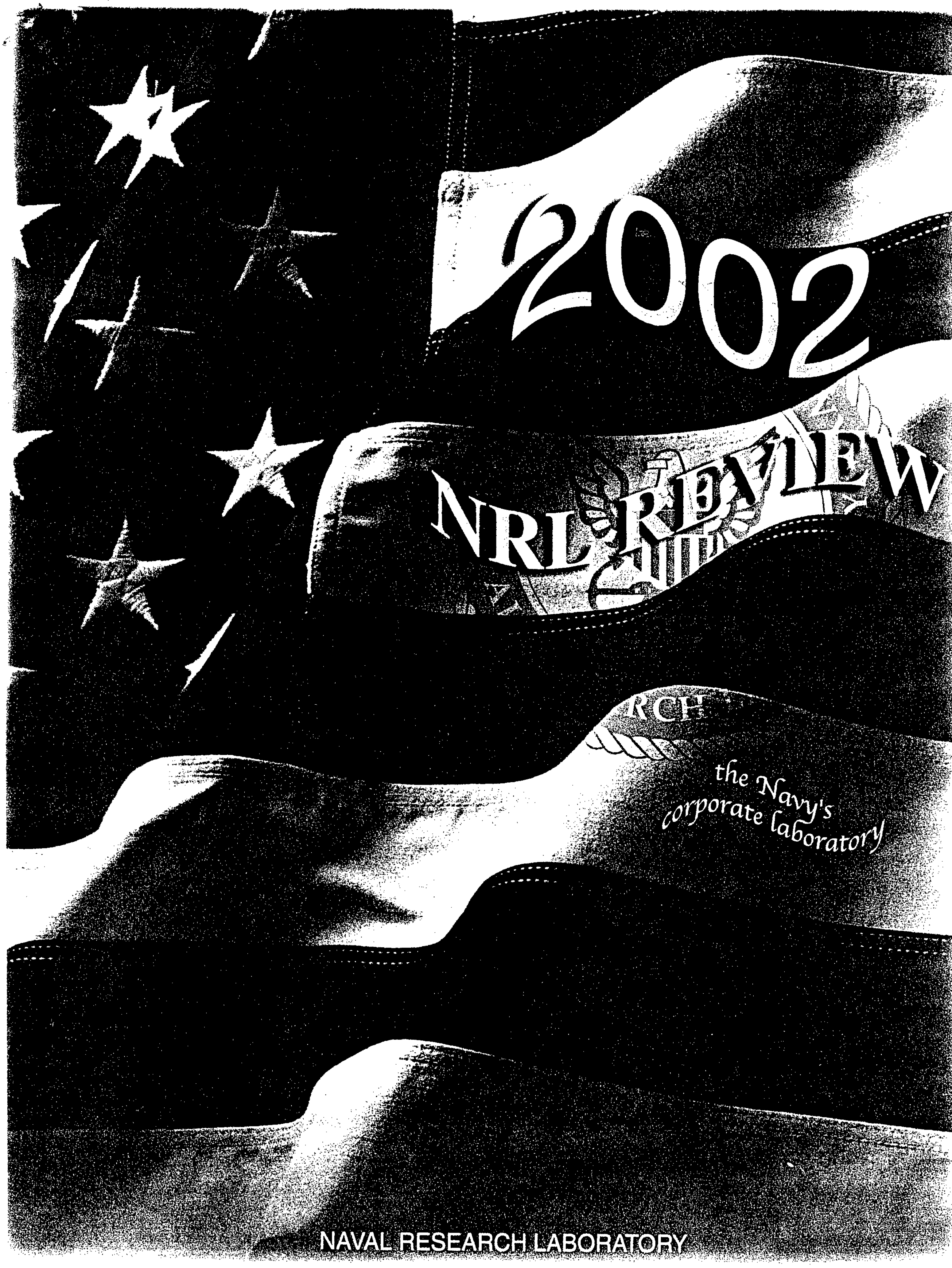
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Anatomy of the Ocean Surface Roughness

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Introduction: Water waves are the roughness components of the ocean surface. Their presence causes wind drag, which is an important topic of air-sea momentum transfer. From a remote sensing point of view, surface roughness is an important parameter quantifying the scattering of electromagnetic waves (including radar and optical waves). Understanding the ocean surface roughness properties is clearly important to many areas of physical oceanography and ocean remote sensing.

The Conventional View: Traditionally, the ocean surface roughness is equated to the mean-square slope of the ocean surface waves. Results from ocean wave research show a logarithmic increase with wind speed of the mean-square slopes computed from well-established spectral models.[1] This result is consistent with the surface roughness data collected by Cox and Munk (referred to as CM hereafter) in slick surface conditions.[2] Although the airborne measurements by CM were conducted more than a half century ago, this data set remains the most comprehensive in terms of the range of wind and wave conditions and the scope of their statistical analysis; they were able to produce coherent slick coverage for wind conditions up to 9 m/s using man-made slicks.

In contrast to the slick cases, the computed mean-square slopes underestimate the surface roughness measured in clean water conditions by a factor of three in medium to high wind conditions (Fig. 1(a)). In most ocean remote sensing applications, this is a serious problem because clean surfaces are encountered more than slick surfaces.

The Missing Elements: CM describe that "... with 200 gallons of this mixture [of 40 percent used crankcase oil, 40 percent diesel oil, and 20 percent fish oil] a coherent slick 2,000 feet by 2000 feet could be laid in 25 minutes, provided the wind did not exceed 20 miles an hour [8.94 m/s]. . . . " The fact that the man-made slick remains coherent in relatively high wind speed conditions offers an important clue about the missing components of the surface roughness—that the presence of surface slicks damps out not only the small-scale surface waves but also the wave breaking event, which is an important element controlling the ocean wave dynamics. Experiments have shown that wave breaking produces enhanced surface roughness. It remains uncertain about the dynamic range (in terms of the upper bound wavenumber) of the CM optical data. By experimentation, we examine cases with cutoff wavenumbers ranging from $2\pi/0.3$ to $2\pi/0.03$ rad/m. The difference between the measured clean water roughness and the mean-square slope is plotted in Figs. 1(b) to 1(d). An interesting trend that becomes apparent is that the breaking roughness displays a robust power-law wind speed dependence $U^{1.5}$.

To test the hypothesis of multiple components in the ocean surface roughness, we examine a different kind of surface roughness data source—the backscattering radar cross sections of a spaceborne altimeter. Based on our earlier study, it is found that due to the presence of ambient roughness on the ocean surface, the wind-induced surface roughness is related to the function defining the upper bound of the scatter plot of radar cross sections σ_0 vs wind speeds U. The wind-generated roughness as a function of wind speed derived from the TOPEX altimeter is plotted in Fig. 2(a), again showing much larger magnitude than the calculated mean square slope (dashed line). The wind-speed dependence of the breaking roughness of the altimeter data also follows $U^{1.5}$ (Fig. 2(b)).

Conclusions: Our recent analysis of ocean surface roughness has led to the conclusion that there are at least three roughness components: the mean-square slope of wind-generated waves, breaking roughness, and ambient roughness. Only the first two components can be related to local wind generation. The former represents the geometric contribution of the wavy surfaces; the latter is a complicated combination of discontinuities and disruptions of the kinematic and dynamic processes associated with wave breaking.

This result has significant implications on the interpretation of ocean remote sensing data, e.g., wind retrieval from altimeter or scatterometer data. Over the years, the analytical calculation of altimeter return from ocean surface cannot produce satisfactory agreement with measurements, and the operational algorithms of wind retrieval rely on empirical functions instead of a physics-based formulation. The discrepancy of the analytical computation can be explained by the failure to account for the ambient component of the ocean surface roughness.

[Sponsored by ONR]

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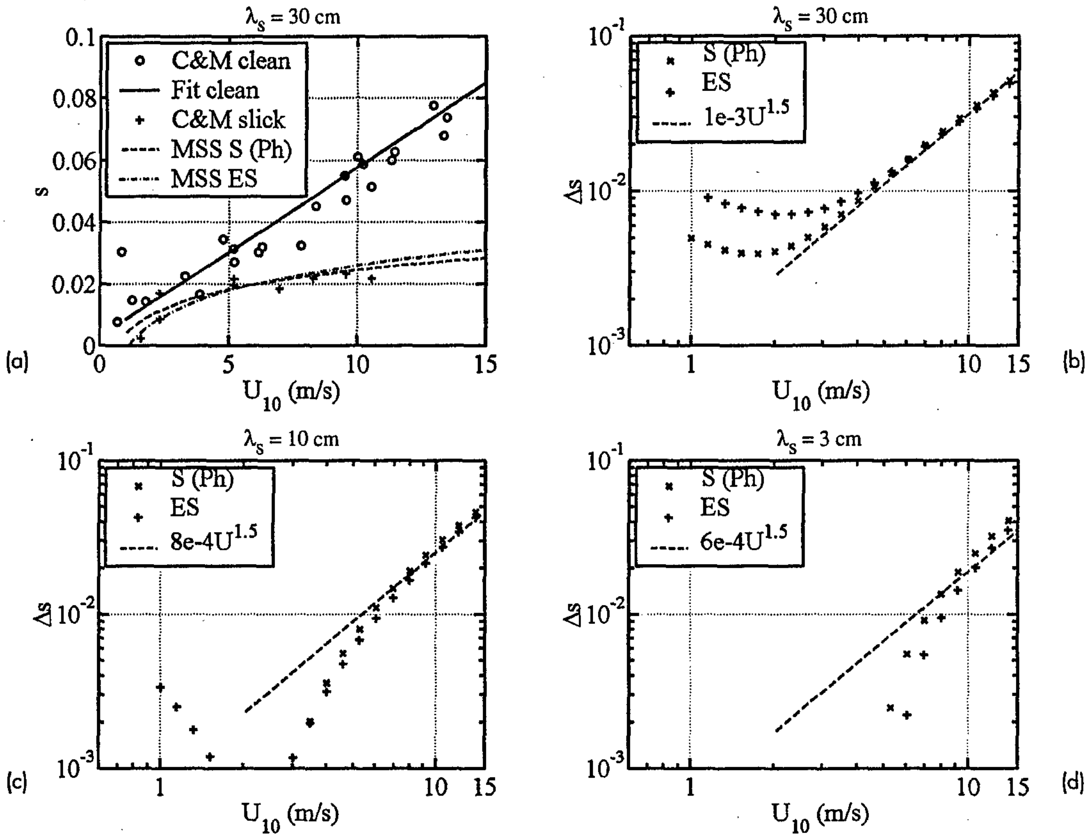

FIGURE 1

(a) The ocean surface roughness measured in clean and slick surface conditions (symbols) reported by Cox and Munk[2] and the comparison with calculated mean-square slopes based on established wave spectral models (curves).[1] (b)-(d) Breaking roughness calculated from the difference of the total roughness (clean water condition) and the mean-square slopes assuming three different cutoff wavenumbers.

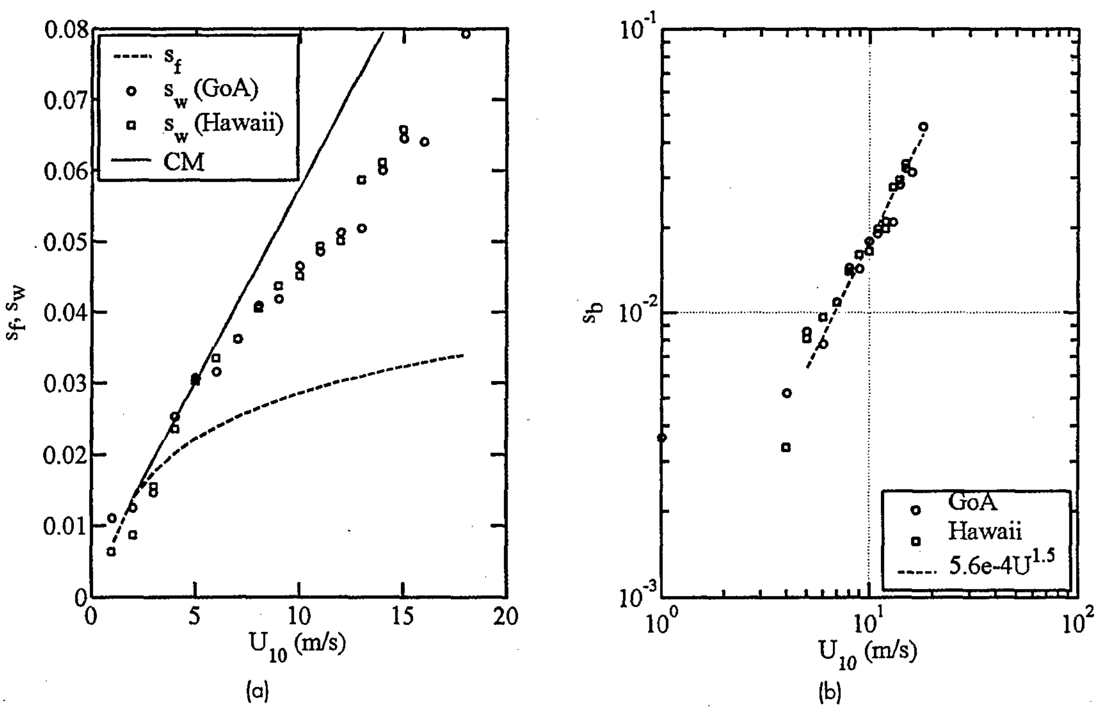

FIGURE 2

(a) Wind-induced roughness (symbols) derived from the TOPEX altimeter data. The calculated mean-square slope is shown with the dashed curve; for reference, the best-fit curve representing the CM clean water data is shown with the solid curve. (b) The breaking roughness derived from the altimeter data.